A Large-Area Modular X-Ray Focusing System

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ABSTRACT

By noting that production of a good surface finish can be separated from production of a desired surface shape, one can exploit the properties of materials to greatly simplify construction of a large-area glancing-reflection x-ray gathering system. This is accomplished by using surfaces of gold, vacuum-evaporated onto thin, annealed glass; the surface of annealed glass is intrinsically smooth. In two different designs, these coated surfaces are arrayed as parallel-plate modules and nested cones, respectively. There are no critical tolerances in arraying the surfaces. Simple tests on working prototypes have shown that a modular gathering system subtending > 1 m^2 input area can easily be built, with $f \approx 5$ and efficiency $\gtrsim 50\%$ for 10-Å x rays. This will greatly simplify spectral and polarization measurements on all the known astronomical x-ray sources and much-more-sensitive sky surveys, and will facilitate μ-mesic atom studies by permitting large solid

angles to be subtended by small detectors located in a low-background region away from the target. The same approach makes feasible a wide range of crude focusing systems, suitable for photons with energy ranging from 0.1 to about 20,-000 eV, which can be of considerable value for improving signal-to-noise ratios in experiments in the vacuum ultraviolet, soft x-ray, and low-energy gamma-ray regions of the electromagnetic spectrum, including possible applications with Mössbauer lines. Glancing angles as small as one milliradian appear practical; not only photons but also low-energy neutrons can be reflected and focused with angles of incidence this small.

Since its inception, the development of the field of
x-ray astronomy has been paralleled by an effort directed
toward the development of instruments tailored to the parti-
cular needs of various types of experiments. Because of the
necessity of carrying the research instruments above the at-
mosphere in rockets and satellites, considerable emphasis has
been placed on the sensitivity and mechanical ruggedness of
the detector systems.

Early work was done using scintillation and gas-filled
counters with collimating slats to limit their field of view.
A large fraction of the total work in this field has been done
using thin-window gas-filled proportional counters with fill-
ing gases and window materials chosen to give a spectral re-
sponse appropriate to the experimental objectives. In order
to make precise x-ray observations of the sun, Giacconi and
Gursky utilized a small glancing incidence x-ray focusing
system invented by Giacconi and Rossi, which allowed them to
achieve much greater resolution than was feasible with simple
collimators.[1] Focusing systems have the great advantage of
permitting several directions to be viewed at the same time,
each with high resolution, by placing several detectors at
the focus, or by using a 'continuous' detector such as film.
The effective area over which data are collected in such a
system is equal to the product of the number of resolved ele-
ments in the focal plane, that is, the number of directions

in which it can look simultaneously, and the effective area over which the focusing system collects radiation and images it on a single detector element. Hereafter, we will call this product the 'data area.'

The first successful astronomical x-ray focuser had an effective area of about 3 cm^2, and an angular resolution of about 15 sec of arc.[1] The system was intended for measurements of the soft (hν < 1 keV) x-ray spectrum of the sun, where flux was not an important limitation. However, for studying x-ray stars, the effective area of such a system is not great enough to overcome the limitations due to the statistical nature of the observations. What is needed is a large effective area, for survey, spectral, and polarization measurements, which has sufficient resolution to distinguish between adjacent sources. This means that much astronomical work could be done with an instrument which had less resolution, provided that its effective area were large enough. Given the time limitations of sounding rocket flights, an effective area of 100-200 cm^2 is necessary. With this large effective area to overcome statistical limitations, it is again reasonable to compute a data area based on the number of resolved elements in the image.

For this effective area, a resolution of about one degree would be adequate to resolve adjacent sources in almost all cases. This would allow spectral and polarization studies and survey work. The resolution is adequate to define the

position of an interesting x-ray source closely enough to permit use of a high resolution x-ray system with smaller effective area, pointed in that direction only for an entire flight, to determine the position to the level of precision necessary for optical identification. In many cases, a resolution of one degree would itself suffice for optical identification. Thus, an instrument with a resolution of about 1/2 to 1 degree and an effective area of 100-200 cm^2, suitable for sounding rocket flights, would be quite useful for x-ray astronomy.

This relaxation of the resolution requirements has an important consequence; it makes possible designs in which the processes of polishing the reflecting surfaces to the extremely high levels necessary for efficient x-ray reflection are separated from the processes of orienting the polished surfaces to converge the incident rays to form an image. This decomposition of the problem has made possible the construction of relatively simple and inexpensive large-area x-ray focusing systems suitable for one-time-only use in sounding rockets. The desired surface smoothness is achieved by using the intrinsic smoothness of certain materials such as glass, and the orientation by use of simple mounting jigs.

When a liquid is allowed to increase its viscosity over a time long compared with the time for viscous damping of mechanical disturbances of its surface, surface tension and viscous damping lead to a final surface which is extremely smooth on a microscopic scale. It is this microscopic, or

local, smoothness which is necessary for x-ray reflection. Glass is an example of a liquid whose viscosity increases to very high values. 'Tension polished' surfaces on glass have proved suitable for reflection of x-rays and for use as a substrate for supporting other reflecting materials, particularly evaporation deposited gold.

In the first tests, thin glass plates coated with gold were held in a parallel-plate configuration by spacer wires placed between the plates. The glass plates were commercially manufactured cover glasses about 0.1 mm thick, 20 mm wide, and 50 mm long, and the wire was ordinary copper wire, straightened by pulling it slightly beyond its elastic limit. The x-rays passed along the length of the plates, which were tilted so that the front edge of one plate just shadowed the back edge of the next plate. In this way, an x-ray entering the system had to make one glancing reflection before leaving the parallel plate assembly. One such modular assembly is capable of bending a parallel beam of x-rays by about three degrees at 1.5 keV/photon. A ring of such modules can be used to deflect different parts of an entering parallel beam toward a common spot, to form a focal spot comparable in area to the cross section of one module (see Fig. 1). Such rings of modules, with the interplate spacing and angle of orientation suitably adjusted, can be nested to subtend an input disc and produce a crude lens. In order to have any off-axis imaging properties, it is necessary to use two reflections in cascade, or

an even number in general, to crudely satisfy the Abbe sine condition. Otherwise, for an odd number of reflections the imaged rays reflected by modules whose plates are roughly parallel to the plane containing the direction of the incident beam and the axis of symmetry of the lens, tend to move off axis in the direction expected for a true lens, while those reflected by modules generally perpendicular to that plane tend to move off axis in the opposite direction.

A test version was made with 15 modules in each of two cascaded rings. Rays entering the system experience two reflections, each with a glancing angle of about 1.5 degrees. This resulted in a system with an $\underline{f}$ number of about five. Tests on this version verified that there are, in fact, no critical tolerances in fabricating such a system, and a larger version with four nested rings was made (see Fig. 2). This has a geometric area of about 300 cm^2, and an estimated effective area of about 150 cm^2. Its diameter is about 35 cm, and its focal length about 125 cm, with focal spot about 2 cm in diameter. It has a resolution of a little less than one degree and a field of view which permits resolution of seven elements in the focal plane (see Fig. 3) (weight 15 kg, vibration tolerance 30 g random, for use in an Aerobee-150 sounding rocket).

One can estimate the area of a simple collimating system which will give the same signal-to-noise ratio as one detector subtending one of the resolved elements of the image.

For these purposes, the noise is the statistical fluctuation in the background cosmic radiation which spuriously triggers the detector. Assuming the same fractional efficiency for an anticoincidence shield guarding the detector independent of size, the signal-to-noise ratio increases as the square root of the area subtended by the detector. In the case of the focusing system, the detector is able to subtend an area of 150 cm^2 with respect to the desired signal, and only about 3 cm^2 for a thin detector with respect to penetrating radiation in cosmic rays. This enhances the signal-to-noise ratio by a factor of 50 over the performance of an unassisted detector of equal area. To achieve a comparable enhancement by increasing the area of a direct viewing collimator type of system, that is, one which subtends equal areas with respect to the desired signal and the penetrating radiation background, it would be necessary to increase its area by a factor of 2500 to 7500 cm^2. Thus, the use of seven small detectors, each subtending one element of resolved image in a mosaic, would give an effectiveness comparable to more than 50,000 cm^2, or 5 m^2. In some respects this does not do justice to the power of the technique: because of the small size of the detectors placed at the focus of such a system, it will in general be possible to shield them from cosmic radiation more effectively than large arrays of counters can be shielded, and the required area for a direct viewing system to be as effective as the focused system increases linearly with the ratio of

effectiveness of the shielding of the small detectors at the
focus to the large array's shielding.

Using the technique of parallel plate modules made from
thin glass, it is feasible to utilize glancing angles as small
as one milliradian. In such a system, the internal area (for
two stages of reflection) is 2000 times the geometrical sub-
tended beam area, and inefficiencies in reflection would re-
quire an internal area 4000 or more times the effective area.
Such small glancing angles are of interest for two reasons:
they permit focusing of x rays and gamma rays of energy up to
about 20 keV, which would allow focusing of some of the inter-
esting Mössbauer lines; and because subthermal and thermal
neutrons can be reflected at glancing angles this small.
There are a number of applications in which signal-to-noise
enhancement can be achieved by use of simple focusing systems
of this type: these include studies of μ-mesic atoms, the
Mössbauer effect, and the spectra of multiply excited atoms
and molecules.

The dependence of high energy cutoff upon angle of re-
flection in a focusing system of the present type can be ex-
ploited to select specific energy ranges. Because absorption
in the interstellar medium is particularly strong for energies
less than about 800 eV, useful information about the inter-
stellar medium, and about the distances to x-ray sources, can
be obtained from observations of the very soft x-ray spectrum
of these astronomical objects. However, because the higher

energy x-rays are absorbed very much less in traversing the distance to us, it is important to ensure that the sensitivity of the complete instrument system to these higher energy photons is very much less than for those with lower energy. One way to do this is to choose angles of reflection sufficiently large that the higher energy x-rays are beyond the limit for total external reflection and they are therefore not focused at all. This gives the advantage of an intensification of the desired signal, accompanied by rejection of the undesired high-energy flux. Measurements of this type, particularly those with very high discrimination against higher energy x rays, are desirable for all astronomical x-ray sources.

For measurement of polarization, one method which has been proposed is the use of Compton scattering of x rays from electrons in a material of low atomic number. The scattering is polarization dependent, and x rays scattered laterally from the target into detectors carry polarization information. For such measurements, it is highly desirable to have a large effective collecting area: the polarization of the radiation is obtained in terms of the difference between the counts recorded by two counters facing adjacent sides of the scatterer, and for this reason the statistical limitation on the measurement is much more severe than for direct observations. It is important to note that a telescope with a true point focus would have no advantage for polarization measurements over the crude lens discussed here. This results from the fact that the scattering block must have a depth determined by the photon mean free

path in the material. Typically this is at least several centi-
meters, and the ratio of scatterer length to diameter must be
about the same as the f number for the lens; otherwise some of
the radiation would be lost. Thus, even with a point focus, the
diameter of the scatterer must be at least two centimeters for
an f = 5 optical system, and the surrounding detectors must be
large enough to encompass such a block. Essentially, the same
size block and detectors would be required for the modular lens.
The latter system would have a much larger effective collecting
area and a correspondingly greater polarization sensitivity.
The true point focus lens would be advantageous for polariza-
tion measurements only if one were to attempt to exploit the
anomalous coherent transmission effect in nearly perfect
crystals.

The system which has been constructed should allow
definite detection of x-ray sources about 0.001 as bright in
the x-ray region as the Crab nebula, which has a flux of five
photons/cm^2/sec at the top of the earth's atmosphere. The
sensitivity depends on the observing time available, and a
three-minute flight in a sounding rocket has been assumed for
this figure. An over-all efficiency of about 16% is readily
obtainable; that is, about 16% of the photons entering the
front of the telescope result in electrical pulses coming
from the detector at the focus. For observation from an or-
bital installation, with a system the same size as the one
which has been constructed, an observing time of about four
weeks would permit a complete sky scan to a sensitivity of

about 0.002 photons/cm^2/sec with a statistical accuracy of 3 σ. This is about 4×10^{-4} of the intensity of the Crab nebula and about 4×10^{-5} of the intensity of Scorpio XR-1. Such a survey with this crude focus might be used to identify interesting objects for study by a maneuverable smaller telescope of the high-resolution type, making the best use of both instruments.

ACKNOWLEDGMENT

REFERENCE

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FIGURE CAPTIONS

FIG. 1.   Schematic of modular focusing technique.

FIG. 2.   A four-ring, two-stage modular x-ray focusing system constructed for use in an Aerobee-150 sounding rocket.   This is an enlarged view showing assembly with gold-coated glass plates spaced by wire held in place by flexible silicone rubber adhesive.

FIG. 3.   Plot of effective area as a function of angle off axis.   This curve shows that seven elements may be resolved in the focal plane.
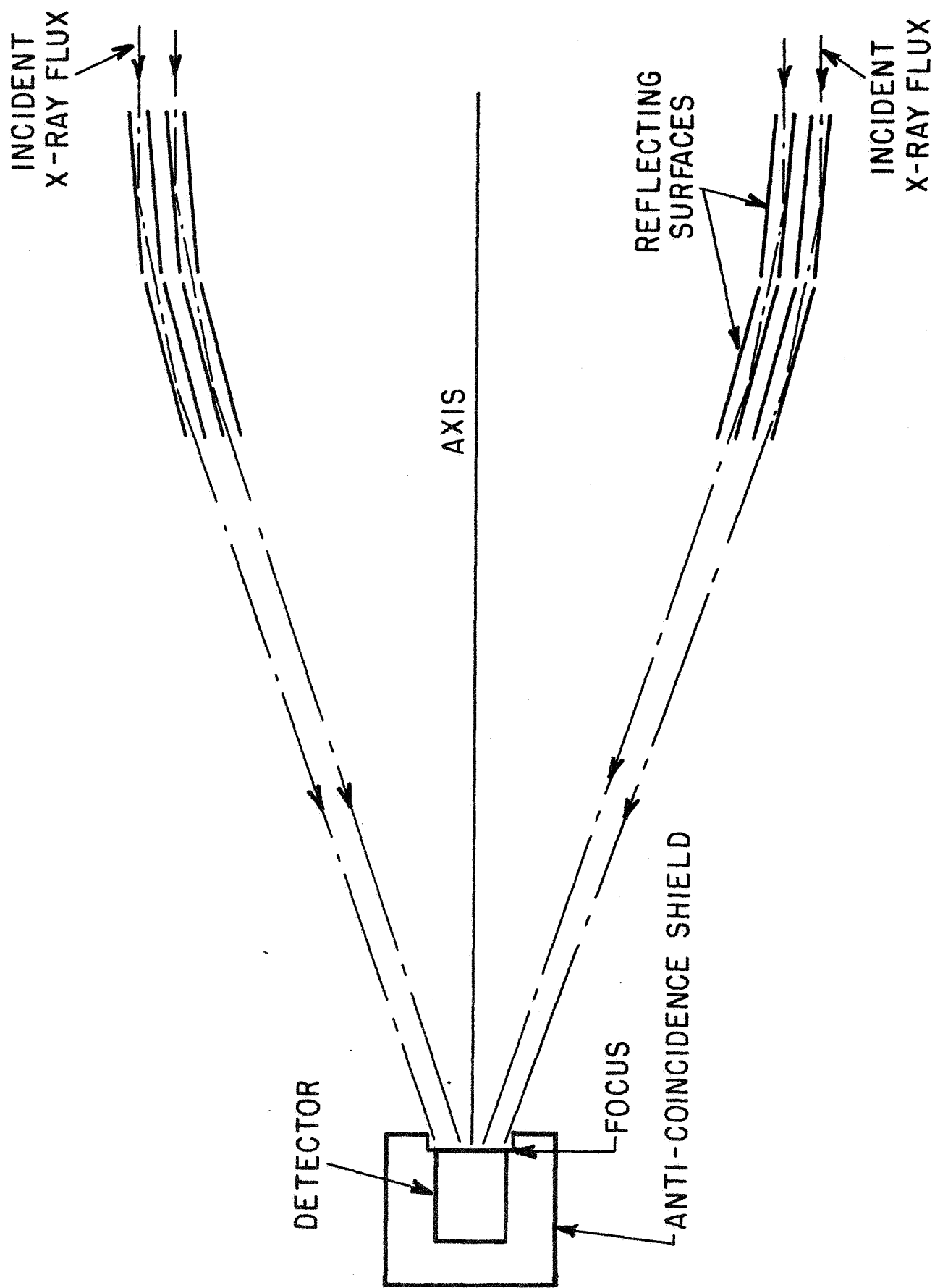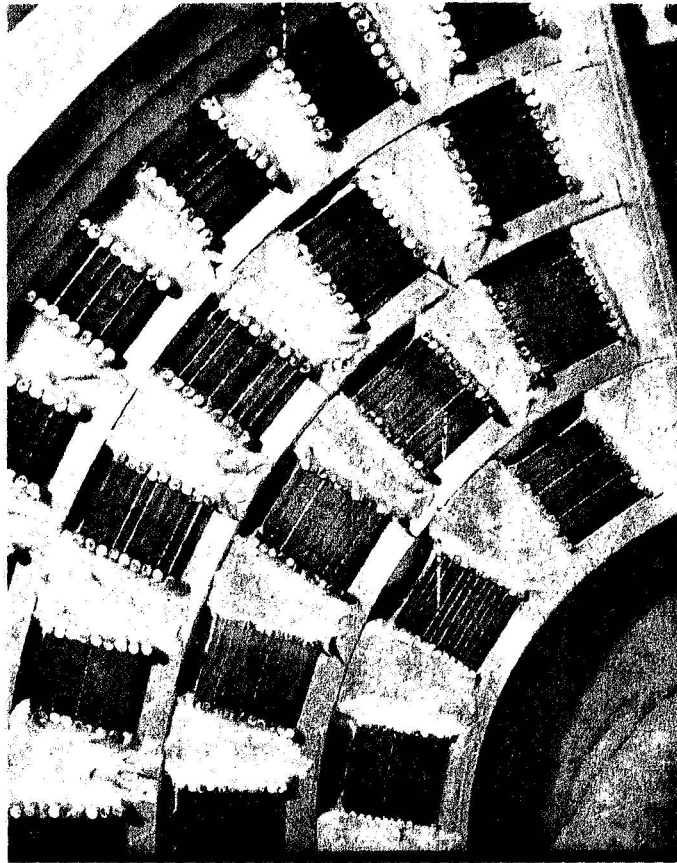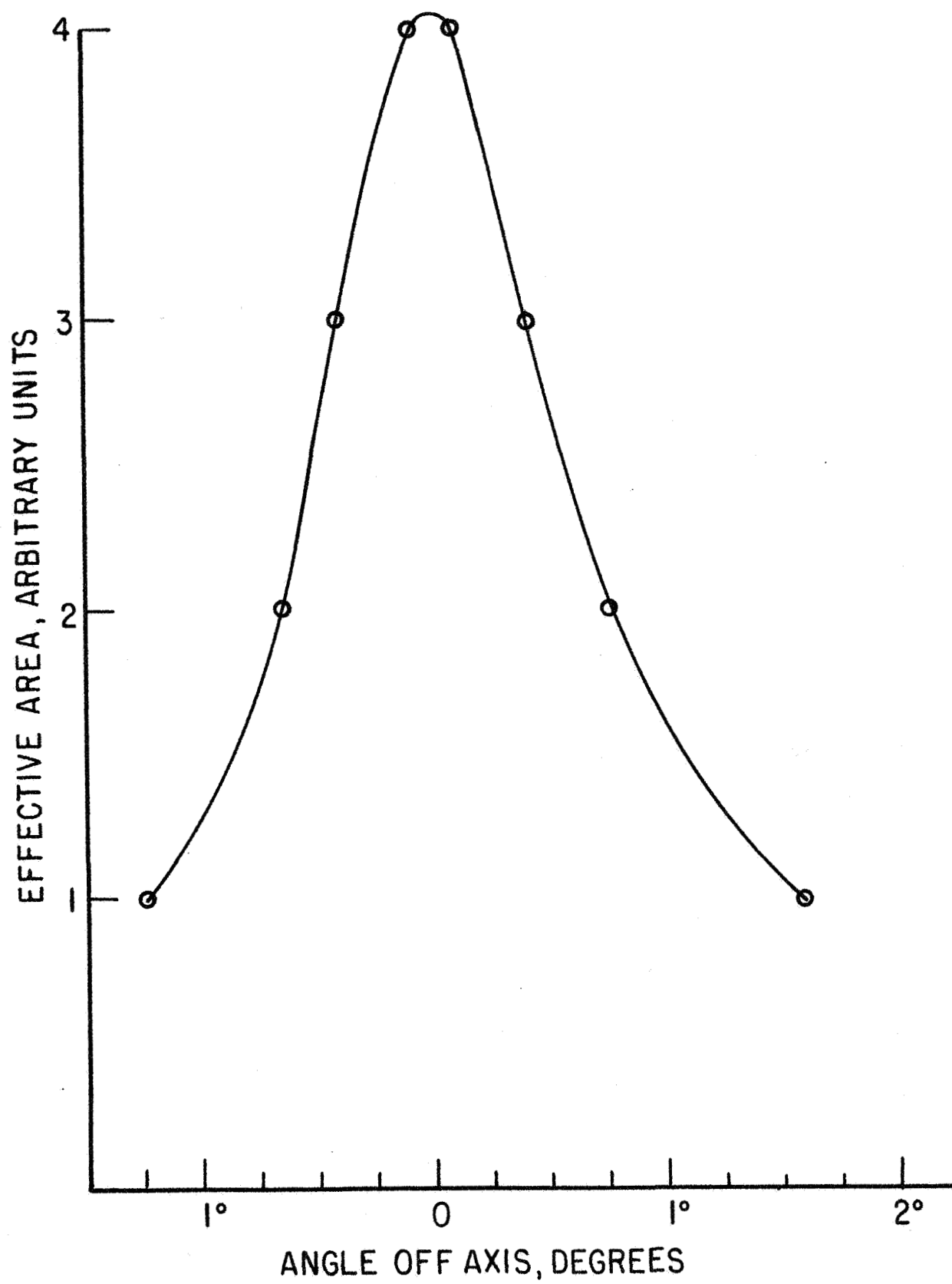
FIG. 1.

FIG. 2.

FIG. 3.